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**METHOD AND DEVICE FOR MAGNETIC MEASUREMENT OF THE  
POSITION AND ORIENTATION OF A MOBILE OBJECT RELATIVE TO  
A FIXED STRUCTURE**

5 The present invention pertains to the precise measurement of magnetic fields and more particularly to the determination of the position and the orientation of a mobile object with respect to a fixed structure.

10 In particular, the invention relates to the determination of the posture of the helmet of a pilot of military aircraft, in which the angular position of a target is determined by aiming, through a system comprising the pilot's helmet VDU.

15 The operation of such a system is recalled briefly below: via an ancillary collimator device, the pilot sees, through his semi-reflecting visor secured to the helmet, on the viewing axis, the image of a reticle  
20 projected to infinity superimposed with the outside scene. When he wishes to designate a target, the pilot makes this reticle coincide with the target and signals that coincidence is achieved, by means for example of a push-button control provided for this purpose.

25 Provided that the exact angular position of the helmet is referenced at the moment that coincidence is signaled, it is possible to determine, with respect to the aircraft, the direction of aim and to designate the  
30 objective to a weapon system, or to point an optical system for example in this direction.

A device for measuring orientation and position of the helmet of the pilot in a reference frame tied to the  
35 aircraft can consist of an orientation and position sensor made up of three orthogonal electromagnetic coils and placed on the helmet, and of an emitter, situated at a fixed point of the cabin, and made up of three other electromagnetic coils.

The method then consists in passing an electric current through each coil of the emitter (forming a substantially orthogonal fixed trihedron). These  
5 currents engender three magnetic fields which are sensed by the coils of the sensor (forming a substantially orthogonal moving trihedron tied to the helmet). The analysis of these magnetic fields makes it possible to determine the position and the orientation  
10 of the moving trihedron with respect to the fixed trihedron.

In this domain of application in particular, it is vital to obtain an accurate measurement of the magnetic  
15 fields emitted by the fixed emitter, and detected by the sensor tied to the helmet, so as to accurately designate, to a weapon system, the objective selected by the pilot.

20 Hitherto, components of high accuracy, sometimes thermostatically controlled, which are able to operate within a wide time duration, have been used for this measurement.

25 A drawback of this prior art technique is that, even with components of high quality and hence of very high complexity and very high cost, it is difficult to attain the very high accuracy required by this domain of application.

30 Another drawback of this prior art technique is that, even with components of high quality and of very high cost, it is difficult to maintain a high level of accuracy over time, on account of the aging of the  
35 components.

Calibration techniques have been proposed, in order to limit these drawbacks. However, the calibration phases presuppose, according to these techniques, the

temporary interruption of emission, and hence of the operation of the sensor. This interruption is not acceptable in numerous situations (decrease in the signal-to-noise ratio), and in particular in the case  
5 discussed above of military equipment, where the signal-to-noise ratio must necessarily be optimized so as to thereby obtain the maximum accuracy.

The applicant has conceived of a much more advantageous  
10 calibration technique by virtue of which the magnetic field measurement can operate in a continuous manner and does not require any preliminary and/or periodic calibration phase during which the measurement would be interrupted.

15 In a magnetic field measurement device comprising at least one measurement acquisition chain, provision is made according to this technique to implement calibration signals which are superimposed on the  
20 signals to be measured and which exhibit spectral components at frequencies distinct from those of the useful signals. It is thus easily possible to calculate an estimate of an electrical quantity representative of the measurement chain, on the basis of the calibration  
25 parameters, without interrupting the measurement, in such a way as to eliminate the uncertainties of measurement and/or the dependence of the measurement on slowly varying parameters, known with insufficient or unknown accuracy, such as for example the resistors for  
30 measuring current and the transfer functions of measurement chains. The transfer function or the calibration output voltage of the chain is preferably chosen as representative electrical quantity.

35 However, this technique takes account only of the calibration of the measurement acquisition chains but not the calibration of the transfer functions of the channels of the sensor.

The subject of the invention is therefore a method and a device for magnetic measurement implementing a complete calibration making it possible to accurately ascertain the complex amplitude of the magnetic fields  
5 to be measured.

In a general manner, if we denote by  $[\vec{B}_c(j\omega)]$  the fields resulting in the sensor frame from the fields emitted by the emitter, the measurements at the outputs of the  
10 channels of the sensor may be written:

$$[\vec{M}(j\omega)] = T(j\omega) [\vec{B}_c(j\omega)]$$

where  $\omega$  in fact represents a set of mutually distinct  
15 frequency terms that are integer multiples of a term  $\omega_0 = \frac{2\pi}{T_{obs}}$  (with  $T_{obs}$  duration of a measurement cycle),

respectively emitted by the emission channels and where  $T(j\omega)$  is a matrix whose terms represent the transfer functions relating outputs and inputs of the sensor.  
20 The diagonal terms of  $T(j\omega)$  are therefore the transfer functions of each channel of the sensor and the off-diagonal terms represent the inter-channel coupling terms. These off-diagonal terms are small by construction of the sensor and will be neglected in the  
25 subsequent description of the invention although the method may be applied in the same manner.

To be able to accurately model  $[\vec{B}_c(j\omega)]$ , it is therefore necessary to accurately ascertain the complex terms of  
30 the matrix  $T(j\omega)$  as a function of the angular frequency, in terms of amplitude and phase.

The subject of the invention is a method and a device whose principle relies on the injection of calibration  
35 signals superimposed with useful signals, which do not modify the estimate of these useful signals and which are perfectly discernible and measured without error,

then on the identification of the transfer function of the sensor so as to correct the measurements by the inverse of the complex transfer function of the corresponding channel.

5

According to the invention, there is therefore provided a method of magnetic measurement of the position and the orientation of a mobile object with respect to a fixed structure, in which a first emitter assembly  
10 includes at least two orthogonal coils for emitting magnetic fields, integral with said fixed structure, which define a reference frame, and means of emission for injecting predetermined emission currents into said coils at first frequencies, in which a second sensor  
15 assembly includes at least two orthogonal coils for detecting magnetic fields, integral with said mobile object, sensor channels with servocontrol loops for producing in feedback coils coupled to said detection coils feedback magnetic fields by injection of  
20 measurement currents and a calibration channel for elaborating at least one calibration voltage, and in which at least one acquisition channel is provided for extracting measurement values of said emission channels, said sensor channels and said calibration  
25 channel and means of calculation and of processing estimate, on the basis of said measurement values, the magnetic fields detected in the second sensor assembly and deduce therefrom the position and the orientation of said mobile object in said reference frame, said  
30 method being characterized in that said calibration voltage comprises only terms with at least two frequencies distinct from said first frequencies and in that said method comprises a step of injecting calibration currents and voltages into said channels of  
35 the sensor so as to produce calibration measurement values identified by their frequency, a step of estimating by the means of calculation the transfer function of each of the sensor channels and a step of deducing by said means of calculation the magnetic

fields detected on the basis of said measurement values and of the inverse of said estimated transfer functions.

5 The invention also provides for such a method in which the servocontrol loops of the sensor channels provide output voltages producing said measurement currents and said measurement currents flow through measurement resistors so as to provide measurement voltages,  
10 characterized in that the calibration voltage is superimposed on said output voltages for the production of said measurement currents, and in that said step of estimating the transfer functions is performed, on the basis of the separation of the calibration frequency  
15 terms in said output voltages, by polynomial approximation for said first frequencies.

According to another aspect of the invention, there is provided a device for the magnetic measurement of the  
20 position and the orientation of a mobile object with respect to a fixed structure, of the type comprising:

- a first emitter assembly including at least two orthogonal coils for emitting magnetic fields, integral with said fixed structure and defining a  
25 reference frame, and means of emission for injecting predetermined currents into said coils at first frequencies and constituting with said coils at least two emission channels;
- a second sensor assembly including at least two  
30 orthogonal coils for detecting magnetic fields, integral with said mobile object, means of measurement by servocontrol loops, for producing in feedback coils coupled to said detection coils feedback magnetic fields by injection of measurement  
35 currents and for constituting with said detection coils at least two sensor channels, and means of calibration comprising a calibration channel for elaborating at least one calibration voltage at second frequencies;

- at least one acquisition channel for measurements for extracting measurement values of said emission channels, said sensor channels and said calibration channel; and
- 5 - means of calculation and processing for estimating, on the basis of said measurement values, the magnetic fields detected in the second sensor assembly and deducing therefrom the position and the orientation of said mobile object in said reference frame,
- 10 characterized in that said second frequencies are distinct from said first frequencies, in that said means of calibration are provided so as to inject calibration currents and voltages into said sensor channels so as to produce calibration measurement
- 15 values identified by their frequencies and addressed to said means of calculation by the acquisition channel or channels and in that said means of calculation and processing are provided so as to estimate the transfer function of each of the sensor channels and to deduce
- 20 the magnetic fields detected from said measurement values and from the inverse of said estimated transfer functions.

The invention will be better understood and other  
25 characteristics and advantages will become apparent with the aid of the description hereinbelow and of the appended drawings where:

- figure 1 is a basic diagram of a device of the type implemented in a helmet sight;
- 30 - figure 2 is a schematic diagram of the architecture of such a device adapted to a disturbed magnetic environment;
- figure 3 is a basic diagram explaining a sensor channel according to the invention;
- 35 - figure 4 is a representation of the channel of figure 3 using Laplace transforms;
- figure 5 is a simplified diagram of the sensor according to the invention considering only the determination of the transfer function of each

channel;

- figure 6 is a diagram taking account moreover of the identification of the variable components of the sensor; and
- 5 - figure 7 is the diagram of a practical embodiment of a magnetic measurement device according to the invention.

As briefly explained hereinabove, the invention relates  
10 to the accurate magnetic measurement of the position and the orientation of a mobile object with respect to a fixed structure. Figure 1 is a basic diagram of such a device.

15 The object thereof consists in determining the position and the orientation of a magnetic sensor 11 in the orthonormal reference frame  $[R]_E$  12 formed by the 3 coils of an emitter 1 of magnetic field  $\vec{B}_E(\vec{x})$ . It will be noted, for the sake of clarity and simplification,  
20 that only one emission coil has been represented in figure 1. The generalization to three coils is immediate.

At the point  $\vec{x}$ , which indicates the position of the  
25 sensor 11 in the reference frame  $[R]_E$ , the induction  $\vec{B}_E(\vec{x})$  is projected onto the 3 axes of the detection and feedback coils 13 of the sensor. The feedback currents  $i_{c1}$ ,  $i_{c2}$  and  $i_{c3}$  implemented in the sensor 11 cancel out these projections, through a servocontrol process known  
30 to the person skilled in the art.  $i_{c1}$ ,  $i_{c2}$  and  $i_{c3}$  therefore represent the measurements of magnetic induction along the directions of the axes of the sensor.

35 Specifically, for an emission on a single coil such as represented in figure 1, it is known that at a point  $\vec{x}$  in space, for an orthonormal emitter and an orthonormal sensor, the sensor 11 measures:



$$\begin{pmatrix} i_{c1} \\ i_{c2} \\ i_{c3} \end{pmatrix} = k [R'_{C/E}] \begin{pmatrix} f_1(\vec{p}) \\ f_2(\vec{p}) \\ f_3(\vec{p}) \end{pmatrix} i_E \quad (1)$$

where  $R'_{C/E}$  is the transposed matrix of the matrix for  
 5 switching from the emitter frame of reference to the  
 sensor frame of reference, and formed of the unit  
 vectors of the sensor axes expressed in the emitter  
 frame of reference and  $k$  a proportionality term  
 dependent on the units chosen,  $f_1(\vec{p}), f_2(\vec{p}), f_3(\vec{p})$  being the  
 10 components of  $\vec{B}_E(\vec{p})$  at the point  $\vec{p}$  in the frame of  
 reference 12  $[R]_E$  formed by the emitter 1 for a unit  
 emission current.

By taking the ratios  $\frac{i_{c1}}{i_E}, \frac{i_{c2}}{i_E}, \frac{i_{c3}}{i_E}$  (where  $i_E$  is the emission  
 15 current), only the information regarding position  $\vec{p}$  and  
 rotation  $X, Y, Z$  of the sensor 11 still remains in the  
 expression for the measurement (1) above. In the more  
 general case of three emissions along the three axes of  
 the emitter, the obtaining of the 3x3 matrix of generic  
 20 term  $i_{ci}/i_{Ej}$ , where  $i$  and  $j$  are indices of value 1 to 3,  
 therefore affords easy access to the orientation and to  
 the position of the sensor 11 in the frame of reference  
 12 of the emitter 1.

25 Figure 2 illustrates the basic architecture of a device  
 as described hereinabove. We consider the general case  
 of use in an environment of magnetic disturbances due  
 for example to the presence of conducting bodies and/or  
 of bodies of ferromagnetic type.

30

A block 1 for generating signals is made up of three  
 channels  $1_1$  to  $1_3$ . Each channel  $1_1$  to  $1_3$  comprises a  
 generator  $11_1$  to  $11_3$  of current  $i_{B1}$  to  $i_{B3}$ , a coil  $12_1$  to  
 123 and a resistor  $13_1$  to  $13_3$ . The flow of the current  
 35 in the coils  $12_1$  to  $12_3$  allows the creation of a

magnetic field  $B_1$  to  $B_3$  respectively for each of the channels  $1_1$  to  $1_3$ . The currents  $i_{B1}$  to  $i_{B3}$  injected into the coils  $12_1$  to  $12_3$  are preferably produced by current generators of internal impedance greater than  $500\text{ k}\Omega$ .

5 According to a preferred mode of embodiment, the current generators  $11_1$  to  $11_3$  are connected to untuned coils. The invention applies of course also to the case where the current generators  $11_1$  to  $11_3$  are connected to tuned coils.

10

Magnetic disturbances, which arise in ferromagnetic materials and/or conducting materials surrounding the helmet viewfinder device illustrated in figure 1, are superimposed on the fields  $B_1$  to  $B_3$  in the form of  
15 disturbing magnetic fields  $B_{p1}$  to  $B_{p3}$ .

The sensor 14 receives the sum of the fields  $B_1$  to  $B_3$  emitted respectively by the channels  $1_1$  to  $1_3$  of the block for generating the signals 1, of the disturbing  
20 fields  $B_{p1}$  to  $B_{p3}$ , and of any radiated disturbances 15  $B_r$ .

A block 16 for calibrating the sensor delivers the calibration signals  $V_{1cal}$ ,  $V_{2cal}$  and  $V_{3cal}$ .

25

On completion of the various processing operations applied to the fields received, the block 20 outputs the matrix  $C_{ij}$  of the emitter-sensor couplings in free space, which makes it possible to calculate in a known  
30 manner the position and the orientation of the sensor 14 in the reference frame of the emitter 1 of the helmet viewfinder device.

The block 20 makes it possible:

- 35 - to separate and measure the measurement and calibration electrical quantities (voltages and currents) by virtue of the fact that they are disjoint in terms of frequency;  
- to model the fields received by iterative techniques;

- to identify the constant fields with the frequency making it possible to estimate the magnetic field emitted in free space by eliminating the disturbing fields;
- 5 - to estimate the position and the orientation of the helmet sight carrying the sensor.

Figure 3 is a more detailed diagram explaining the principle of a sensor channel of the device according  
10 to the invention.

We wish to measure the ambient magnetic induction  $B_{ext}$  at the level of the sensor. To do this, we use, for each channel, a detection coil  $Bb_d$  coiled at the same  
15 time as an associated feedback coil  $Bb_{CR}$  around a common core 21 made of very permeable magnetic material ( $\frac{\mu}{\mu_0} \gg 1$ ). It is known that magnetic induction is related to the magnetic field by the relation  $B_{ext} = \mu H_{ext}$ . Across the terminals of the detection coil  
20  $Bb_d$  we measure the flux variation:

$$e = - \frac{d\phi}{dt} = - N_d S_d \frac{d(B_{ext} - B_{CR})}{dt}$$

where  $N_d$  and  $S_d$  represent the number of turns and their  
25 mean area. This measurement is performed with the aid of a servocontrol loop comprising an amplifier 22 with transfer function  $KA(j\omega)$  receiving the voltage  $e$  tapped off from the terminals of a capacitor  $C$  added in order to greatly reduce the detection coil's inherent  $Q$   
30 factor, a corrector network 23 making it possible to stabilize the servocontrol loop, an amplifier 24 of gain  $A_2$ , and a current generator 25 with a constant pure resistance  $R_s$  which fixes the voltage/current transfer coefficient at the amplifier 24. The current  
35 generator 25 generates the feedback current  $i_c$  which is injected into the feedback coil  $Bb_{CR}$ . This current  $i_c$  is sent to ground through a measurement resistor  $R_M$ . On

the terminal 27 is a measurement voltage  $V'_c$  representing the value of the measurement current  $i_c$ . Finally, according to a characteristic of the invention, a calibration voltage  $-V_{cal}$ , applied to the terminal 26, is superimposed on the output voltage  $V_c$  of the sensor channel, present at the input of the amplifier 24.

The feedback magnetic induction  $B_{CR}$ , produced by the injection of the current  $i_c$ , in the coil  $Bb_{CR}$  may be written:

$$B_{CR} = N_{CR} \mu k_B i_c = \mu k_{CR} i_c$$

where  $N_{CR}$  is the number of turns per unit length and  $k_B$  is a constant dependent on the units used, with by definition  $H_{CR} = \frac{B_{CR}}{\mu} = k_{CR} i_c$ .

If the servocontrol operates correctly, we have  $B_{ext} \cong B_{CR}$  and the voltage  $\underline{e}$  tends to zero.

Represented in figure 4 is the diagram of the channel of figure 3 using Laplace transforms of the time variables to pass to the transfer functions. To determine the transfer function as a function of the angular frequency, it suffices to put  $p = j\omega$ . In this representation,  $K$  is a constant static gain proportional to the product  $N_d S_d \mu(p)$ .  $A_2(p)$  is the complex gain of the amplifier 24. As a function of the quality and hence of the cost of this amplifier, the gain may be constant throughout the operating band as a function of  $\omega$ , constant as a function of the environment or else non-constant.

As seen in the introduction, it is necessary to accurately ascertain the complex transfer functions of each of the channels of the sensor so as to obtain the values  $H_{ext}$  which are the inputs that one seeks to

measure. The voltage  $V_{cal}$  is a secondary input that is appended to calibrate the system according to the invention.

5 By putting:

$$G(j\omega) = A(j\omega)C(j\omega)$$
$$R(j\omega) = k_{CR} \frac{A_2(j\omega)}{R_s}$$

10 we obtain:

$$T_v(j\omega) = \frac{KGR}{1 + KGR}$$

Now, we can write:

15

$$V_c(j\omega) = -T_v(j\omega)V_{cal}(j\omega) + T_v(j\omega)\left(\frac{H_{ext}(j\omega)}{R(j\omega)}\right) \quad (a)$$

$$V'_c(j\omega) = R_M \left[ (1 - T_v(j\omega)) \frac{A_2(j\omega)}{R_s} V_{cal}(j\omega) + T_v(j\omega) \left( \frac{H_{ext}(j\omega)}{k_{CR}} \right) \right] \quad (b)$$

As may be noted, by virtue of the superposition of  
20 calibration signals  $V_{cal}(j\omega_{cal})$  at angular frequencies  $\omega_{cal}$  different from the angular frequencies  $\omega_u$  of the useful signals of  $H_{ext}(j\omega_u)$  emitted by the emitter, we can separate the frequency terms (for example by FFT, standing for "Fast Fourier Transform", or by  
25 synchronous detection) and obtain the measurement of the transfer function  $T_v(j\omega)$ . Specifically, on the basis of equation (a) by isolating the terms of angular frequency  $\omega_{cal}$ , we have:

30 
$$V_c(j\omega_{cal}) = -T_v(j\omega_{cal})V_{cal}(j\omega_{cal})$$

We can then identify the estimated value of  $T_v$ :

$$\widehat{T_v(j\omega)} = F(V_c(j\omega_{cal}), V_{cal}(j\omega_{cal}), j\omega)$$

35

where  $F$  indicates an interpolation model such as a polynomial approximation.

On the basis of this estimated value we can isolate in  
5 relation (a) for the angular frequencies  $\omega_u$ :

$$V_c(j\omega_u) = \widehat{T_v(j\omega_u)} \frac{H_{ext}(j\omega_u)}{R(j\omega_u)}$$

$$\text{hence } \widehat{H_{ext}(j\omega_u)} = R(j\omega_u) \frac{V_c(j\omega_u)}{\widehat{T_v(j\omega_u)}}$$

10

The problem which then arises is that the term  
 $R(j\omega_u) = \frac{k_{CR} A_2(j\omega_u)}{R_s}$  is not identified. Specifically  $k_{CR}$  is

regarded as constant and identifiable in the factory  
since, being dimensionally equivalent to a number of  
15 turns per unit length, it is time-invariant and  
independent of the temperature and environmental  
conditions. On the other hand, this is not the case for  
the resistance  $R_s$  or for the gain  $A_2$ . Now, these  
components condition the accuracy of the parameters  
20 that one seeks to measure.

It is therefore necessary to provide a device having  
suitable calibration to determine these components in  
each channel.

25

Figure 5 illustrates a simplified diagram making it  
possible to identify certain important elements of each  
channel of the sensor.

30 Using the indices 1 to 3 for the three channels of the  
sensor corresponding to three orthogonal detection  
coils, the amplifier 22/corrector 23 assembly of figure  
4 has been shown diagrammatically by a block,  
respectively  $Dv1$  to  $Dv3$ , providing an output voltage  $V_{c1}$   
35 to  $V_{c3}$ . The assembly 24 of figure 4 is shown  
diagrammatically by an amplifier 241 to 243 of gain

$A_{21}(j\omega)$  to  $A_{23}(j\omega)$ , a resistance  $R_{s1}$  to  $R_{s3}$  and a current generator providing the feedback current  $i_{c1}$  to  $i_{c3}$  to the feedback coils  $Bb_{CR1}$  to  $Bb_{CR3}$ . A measurement resistor  $R_M$  makes it possible to address the measurement voltage  $V'_{cal}$  to an acquisition path including the amplifier 28 of gain  $A_E(j\omega)$  and which provides, after processing, a digitized value  $V'_{Ncal}$  at output. A second input of the amplifier 28 is either grounded, or receives a calibration value  $V_{cal4}$ . Calibration voltages  $-V_{cal1}$  to  $-V_{cal3}$  are applied to the inverse inputs of the amplifiers 241 to 243.

In the factory, the output voltages  $V_{c1}$  to  $V_{c3}$  are grounded. Denoting by  $i$  the index of the channels of the sensor, we alternately apply  $V_{cali} = V_{cal}(j\omega_{cal})$  to the input of each channel while the calibration inputs of the other channels are grounded. We have:

$$V'_{cal}(j\omega_{cal}) = R_M \left( \frac{V_{cali} \cdot A_{2i}(j\omega_{cal})}{R_{si}} \right)$$

20

from which we deduce  $\frac{R_M}{R_{si}} A_{2i}(j\omega)$  for each channel. However

if the gain  $A_{2i}(j\omega)$  varies in problematic proportions, we must then call upon the combination of relations (a) and b) above. As already mentioned, (a) provides  $T_v(j\omega)$ . By performing the frequency separation of the signals according to the angular frequency  $\omega_u$  or  $\omega_{cal}$ , relation (b) yields:

$$V'_c(j\omega_{cal}) = R_M (1 - T_v(j\omega_{cal})) \frac{A_2(j\omega_{cal})}{R_s} V_{cal}(j\omega_{cal})$$

30

hence:

$$A_2(j\omega_{cal}) \frac{R_M}{R_s} = \frac{1}{1 - T_v(j\omega_{cal})} \frac{V'_c(j\omega_{cal})}{V_{cal}(j\omega_{cal})}$$

and as:

$$\widehat{T_v(j\omega_{cal})} = - \frac{V_c(j\omega_{cal})}{V_{cal}(j\omega_{cal})}$$

we obtain:

5

$$A_2(j\omega_{cal}) \frac{R_M}{R_s} = \frac{V'_c(j\omega_{cal})}{V_{cal}(j\omega_{cal}) - V_c(j\omega_{cal})}$$

From this we deduce  $\widehat{A_2(j\omega) \frac{R_M}{R_s}}$  by polynomial approximation in the same manner as for  $\widehat{T_v(j\omega)}$ .

10

However, this solution makes it possible to take account of the aging over time of the components involved, but if the parameters  $A_2$ ,  $R_M$ ,  $R_{si}$  vary during the mission as a function of temperature, this solution requires that the measurements be stopped in order to perform the calibration ( $V_{ci}$  grounded), this being contrary to the aim sought in the invention. This leads us therefore to the diagram, in accordance with the principle of figure 3, described in figure 6 but where  $i_{c1}$  to  $i_{c3}$  represent the sum of the currents, one produced by the voltage of the sensor  $V_{ci}$  and the other by the calibration voltage. In this diagram, the output quantity is the voltage  $V'_{ci}$  instead of  $V_{ci}$ .

15

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If it is considered that, in each emission coil of index  $j$  (with  $j$  taking the values 1 to 3), there flows an emission current of angular frequencies  $\omega_{j,k_j}$  where  $k_j$  varies from  $K_j$  to  $K_{jmax}$ , all these angular frequencies being mutually distinct and distinct from the calibration angular frequencies  $\omega_{cal}$ , we can write on the basis of relation (b) for sensor channel  $i$ :

$$V'_{ci}(j\omega_{j,k_j}) = R_{Mi} \left[ \widehat{T_v(j\omega_{j,k_j})} \right] \frac{H_{exti}(j\omega_{j,k_j})}{k_{CR}}$$

35 i.e.:



$$V'_{ci}(j\omega_{j,k_j}) = \frac{R_{Mi}}{k_{CRI}} \left[ T_v(j\omega_{j,k_j}) \right] i_{Ej}(j\omega_{j,k_j}) H_{ext i Norm}(j\omega_{j,k_j})$$

where:  $H_{ext i Norm}$

5

is the normalized value of the field emitted for an emission current of 1 ampere.

10 In the subsequent description and for simplicity the useful angular frequencies  $\omega_{j,k_j}$  will no longer be denoted but we shall simply denote  $\omega_u$  just as we denote  $\omega_{cal}$  for the calibration angular frequencies, given that all these angular frequencies are distinct and frequency-separable.

15

As may be seen in the last relation hereinabove giving  $V'_{ci}$ , it will be possible to accurately ascertain  $H_{ext Norm}$  on condition that  $R_{Mi}$  and  $i_{Ej}$  are identified. To do this, we refer to the modified diagram of figure 6, 20 where we find, partially, the three emission channels of the emitter and the three sensor channels. We have, moreover, detailed a calibration channel and the common acquisition channel. The calibration channel comprises in series a digital/analog converter  $CNA_{cal}$ , a sample- 25 and hold module B1 with period  $T_E$ , a filter 30 with transfer function  $F_{cal}(j\omega)$  providing a calibration voltage  $V_{cal}$  on the basis of the digital value  $V_{calN}$ , the whole of this chain having a transfer function  $G_{cal}(j\omega)$ . A calibration current  $i_{cal}$  is provided on the basis of 30 the voltage  $V_{cal}$  with the aid of a resistor  $R_{cal}$  and of a current generator.

The acquisition channel, with transfer function  $G_{acq}(j\omega)$ , comprises an amplifier 28 of gain  $A_E$ , a hold 35 module B1 and an analog/digital converter  $CAN_E$  to provide a measurement digital voltage value  $V_{EN}$ . The direct input of the amplifier 28 is linked by a switch

32 to one of the contacts 1 to 4, making it possible to link in multiplex mode the acquisition channel to the measurement voltage of one of the three sensor channels or of the sum of the three emission channels. The inverse input of the amplifier 28 is linked by a switch 33 either to ground 6, or by the contact 5 to the calibration voltage  $V_{cal}$ . By connecting the amplifier 28 only to ground via the contact 6, it is possible to measure the acquisition chain's own noise.

10

After a calibration cycle where  $V_{cal}$  is injected via the contact 5, then where the current  $i_{cal}$  is injected sequentially onto the measurement resistors  $R_{M1}$  to  $R_{M3}$  and  $R_E$ , the following measurements are available:

15

$$V_{EN}^{(5)}(j\omega) = G_{acq}(j\omega) G_{cal}(j\omega) V_{calN}(j\omega) \quad (c)$$

$$V_{EN}^4(j\omega) = G_{acq}(j\omega) R_E \left[ i_{E1}(j\omega_{u1}) + i_{E2}(j\omega_{u2}) + i_{E3}(j\omega_{u3}) + G_{cal}(j\omega_{cal}) \frac{V_{calN}(j\omega_{cal})}{R_{cal}} \right] \quad (d)$$

20

$$V_{EN1}^{(1)}(j\omega) = G_{acq}(j\omega) R_{M1} \left[ i_{c1} + G_{cal}(j\omega_{cal}) \frac{V_{calN}(j\omega_{cal})}{R_{cal}} \right] \quad (e.1)$$

$$V_{EN2}^2(j\omega) = G_{acq}(j\omega) R_{M2} \left[ i_{c2} + G_{cal}(j\omega_{cal}) \frac{V_{calN}(j\omega_{cal})}{R_{cal}} \right] \quad (e.2)$$

$$V_{EN3}^3(j\omega) = G_{acq}(j\omega) R_{M3} \left[ i_{c3} + G_{cal}(j\omega_{cal}) \frac{V_{calN}(j\omega_{cal})}{R_{cal}} \right] \quad (e.3)$$

25

It is clear that the currents  $i_{c1}$ ,  $i_{c2}$  and  $i_{c3}$  contain all the components at the angular frequencies  $\omega_{1,k_1}$  to  $\omega_{3,k_3}$  that are mutually distinct and distinct from the components at the angular frequencies  $\omega_{cal}$ . It is therefore possible to separate them from one another. Thus the right-hand side of equation (d) can be subdivided into two terms  $G_{acq}(j\omega_u) R_E \sum_j i_{Ej}(j\omega_{uj})$  that will

30

be designated by  $V_{ENI}^{(4)}$  and  $G_{acq}(j\omega_{cal}) R_E G_{cal}(j\omega_{cal}) \left[ \frac{V_{calN}(j\omega_{cal})}{R_{cal}} \right]$   
that will be designated by  $V_{ENcal}^{(4)}$ .

The same notation will be used for relations (e.1) to  
5 (e.3) which will be written with two terms  $V_{ENI}^{(i)}$  and  $V_{ENcal}^{(i)}$ .

Finally relation (c) will have just a single term  
written  $V_{ENcal}^{(5)}$ .

10 From all these relations we easily deduce that:

$$\frac{R_E}{R_{cal}} = \frac{V_{ENcal}^{(4)}}{V_{ENcal}^{(5)}} \quad \frac{R_{M1}}{R_{cal}} = \frac{V_{EN1cal}^{(1)}}{V_{ENcal}^{(5)}}$$

$$\frac{R_{M2}}{R_{cal}} = \frac{V_{EN2cal}^{(2)}}{V_{ENcal}^{(5)}} \quad \frac{R_{M3}}{R_{cal}} = \frac{V_{EN3cal}^{(3)}}{V_{ENcal}^{(5)}}$$

15

hence:

$$\frac{R_{M1}}{R_E} = \frac{V_{EN1cal}^{(1)}}{V_{ENcal}^{(4)}} \quad (f)$$

20 and similar relations for  $\frac{R_{M2}}{R_E}$  and  $\frac{R_{M3}}{R_E}$ .

As we have seen, for  $\omega_{uj}$ :

$$V_{ENI}^{(i)} = G_{acq} R_{Mi} i_{ci}$$

25

Now, from (b) we derive, again for  $\omega_{uj}$ :

$$i_{ci} = T_{vi} \frac{H_{ext i}}{k_{CRi}}$$

30 i.e.:

$$V_{ENI}^{(i)} = G_{acq} R_{Mi} \frac{i_{Ej}}{k_{CRi}} H_{ext i Norm} \widehat{T_{vi}} \quad (g)$$

From relation (d) for  $\omega_{uj}$ , we obtain:

$$5 \quad V_{ENI}^{(4)} = G_{acq} R_E i_{Ej} \quad (h)$$

Combining (g) and (h), we have:

$$V_{ENI}^{(i)} = \frac{\widehat{R_{Mi}}}{R_E} \frac{V_{ENI}^{(4)}}{k_{CRi}} \widehat{T_{vi}} H_{ext i Norm} \quad (i)$$

10

the ratios  $\frac{R_{Mi}}{R_E}$  are identified by relations (f), hence:

$$V_{ENI}^{(i)}(j\omega_{uj}) = \left( \frac{\widehat{V_{ENI}^{(i)}}}{V_{ENI}^{(4)}} \right) \frac{V_{ENI}^{(4)}(j\omega_{uj})}{k_{CRi}} \widehat{T_{vi}}(j\omega_{uj}) H_{ext i Norm} \quad (j)$$

15 these terms  $V_{ENI}^{(i)}(j\omega_{uj})$  form a matrix with nine terms, which depend only on  $k_{CRi}$  since all the other factors are identified. In fact,  $k_{CRi}$  may be regarded as invariant for the three channels of the sensor.

20 Hence, from relation (j) we derive the expression for the desired outputs:

$$H_{ext i}(j\omega_{uj}) = A^{-1} B^{-1} \widehat{T_{vi}^{-1}}(j\omega_{uj}) \quad (k)$$

25 with  $T_v^{-1} = \frac{1}{\rho_T} e^{-j\phi_T}$  if we write  $T_v$  in the conventional complex form  $T_v(j\omega) = \rho_T(j\omega) e^{j\phi_T(j\omega)}$

$$A^{-1} = \frac{V_{ENI}^{(4)}}{V_{ENI}^{(i)}} \text{ frequency-constant}$$

$$30 \quad B^{-1} = k_{CRi} \frac{1}{\rho_j} e^{-j\phi_j}$$

$$\text{if } V_{ENI_j}^{(s)}(j\omega_{uj}) = \rho_j(j\omega_{uj}) e^{j\phi_j(j\omega_{uj})}$$

Thus, the final relation (k) shows that we have indeed compensated for the measurement of the magnetic field with the aid of the inverse of the transfer function of the channel of the sensor.

The embodiment of figure 6 that has just been analyzed is based on the use of a single acquisition channel for all the measurements, this having an obvious advantage of simplicity.

However, this presupposes its use according to a sampling sequence with a period  $T'_E$  such that:

15

$$T'_E = \frac{T_E}{N_a}$$

where  $N_a$  is the number of different channels to be acquired during the period  $T_E$ .

20

If the response time of  $G_{acq}(j\omega)$  is too long with respect to  $T'_E$ , it will then be necessary to adopt the diagram of the embodiment of figure 7.

25 In this figure 7, four acquisition channels with amplification/filtering must be provided:

- three acquisition channels for the measurement currents  $i_{ci}$  operating with the period  $T_E$  in a continuous manner (if it is fast enough, it is possible to use just a single converter CAN multiplexing the three filtered and sampled/held channels at the same instant);
  - a multiplexed acquisition channel operating only on the calibration at a low rate, this not being problematic for identifying slowly varying parameters.
- 35

The three sensor channels therefore each comprise, as already described, a detection coil,  $Bb_{d1}$  to  $Bb_{d3}$ , an amplifier/corrector assembly, 41 to 43, providing the output voltage  $V_{c1}$  to  $V_{c3}$ , an amplifier  $A_{21}$  to  $A_{23}$  receiving the output voltage on an input and the calibration voltage via a switch 44 to 46 on the other input, a feedback current generator  $i_{c1}$  to  $i_{c3}$ , a feedback coil  $Bb_{CR1}$  to  $Bb_{CR3}$  and a resistor  $R_{M1}$  to  $R_{M3}$  for measuring the feedback current on which it is possible to superpose the calibration current  $i_{ca1}$  via a switch 51 to 53. To each of the channels of the sensor there corresponds a measurement acquisition channel  $G_{acq1}$  to  $G_{acq3}$  comprising an amplifier  $A_{m1}$  to  $A_{m3}$ , a filter  $F_1(j\omega)$  to  $F_3(j\omega)$ , a hold module B1 and an analog/digital converter CAN so as to provide the digitized measurement voltage  $V'_{c1N}$  to  $V'_{c3N}$ . Moreover, the emitter channels partially represented are connected so as to send the emission currents  $i_{E1}$  to  $i_{E3}$  to a measurement resistor  $R_E$  on which may also be superposed the calibration current by the switch 54, this resistor being linked to the contact 4 of a switch 55. This switch 55 makes it possible to link the input of a fourth acquisition channel, multiplexed but otherwise similar to the first three channels, to the measurement voltages on the measurement resistors via the contacts 1 to 4, to the calibration voltage via the contact 5, to the ground via the contact 6 and to the output voltages of the three sensor channels via the contact 7 and the switch 56.

All the digitized measurement values are sent to a processor 60 which performs the various measurement and calibration and frequency-separation operations mentioned in the relations above and deduces therefrom the position and the orientation P/O of the sensor, while providing the control signals Ctl necessary for the operation of the assembly and the calibration value  $C_{calN}$  and the periods  $T_E$  and  $T'_E$ .

Thus, it may be seen that, by way of the switch 56, of the acquisition channel  $G_{acq4}$  and of the contacts 7 and 5 of 55, it is possible to determine  $T_{v1}$ ,  $T_{v2}$  and  $T_{v3}$  according to relation (a). Moreover, the acquisition channel  $G_{acq4}$  makes it possible to calibrate, according to relation (f), the values  $\frac{R_{M1}}{R_E}$  to  $\frac{R_{M3}}{R_E}$ . The acquisition and calibration cycles above are independent of the cycles of the continuous measurement of the currents flowing through  $R_{M1}$  to  $R_{M3}$  via the first three channels.

10

With respect to figure 6, it is noted that there are three acquisition channels  $G_{acqi}$   $i$  from 1 to 3, that are mutually distinct and also different from the calibration channel  $G_{acq4}$ . It is shown hereinbelow that the configuration of figure 7 completely solves the problem raised. The various equations available are as follows:

15

➤ calibration:

20

- switch 55, measurements (1), (2), (3), (4):

$$V_{ENcal}^{(4)} = \frac{R_E}{R_{cal}} G_{acq4} V_{cal} \quad (1)$$

$$25 \quad V_{ENcal}^{(i)} = \frac{R_{Mi}}{R_{cal}} G_{acq4} V_{cal} \quad \text{for } i = 1 \text{ to } 3 \quad (m)$$

From this we deduce:

30

$$\frac{R_{Mi}}{R_E} = \frac{V_{ENcal}^{(i)}}{V_{ENcal}^{(4)}} \quad \text{for } \omega = \omega_{cal}$$

- measurements of the channels  $V'_{ciN}$

$$V'_{ciNcal} = G_{acqi} \frac{R_{Mi}}{R_{cal}} V_{cal} \quad \text{for } i = 1 \text{ to } 3 \quad (n)$$

35 Combining (m) and (n) we obtain:

$$\frac{G_{acq\ i}}{G_{acq\ 4}} = \frac{V_{ciNcal}}{V_{ENcal}^{(i)}} \quad \text{for } \omega = \omega_{cal} \quad (o)$$

From these expressions we deduce the estimates via  
5 approximation functions in the frequency domain as  
described previously for:

$$\frac{\widehat{G_{acq\ i}}}{\widehat{G_{acq\ 4}}} \text{ and } \frac{\widehat{R_{Mi}}}{R_E}, \text{ the latter being frequency-invariant}$$

10 ► measurements:

For the useful frequencies to be measured  $\omega = \omega_{uj}$ , we have  
measurements for  $i$  from 1 to 3:

$$15 \quad V_{ciN} = G_{acq\ i} \cdot R_{Mi} \cdot T_{vi} \cdot \frac{H_{ext\ i}}{k_{CRi}} \quad (p)$$

$$V_{ciN} = G_{acq\ i} \cdot R_{Mi} \cdot T_{vi} \cdot \frac{H_{ext\ i\ norm}}{k_{CRi}} \cdot i_{Ej}$$

$$V_{ciN} = \frac{G_{acq\ i}}{G_{acq\ 4}} \cdot \frac{R_{Mi}}{R_E} \cdot T_{vi} \cdot \frac{H_{ext\ i\ norm}}{k_{CRi}} \cdot V_{ENlj}^{(4)}$$

20

$$H_{ext\ i\ norm} = k_{CRi} \left( \frac{G_{acq\ i}}{G_{acq\ 4}} \cdot \frac{R_{Mi}}{R_E} \cdot T_{vi} \cdot V_{ENlj}^{(4)} \right)^{-1} V_{ciN} \quad (q)$$

It is appreciated that in this expression the term  
between brackets is deduced entirely from the  
25 calibrations,  $k_{CRi}$  being regarded as known and constant.  
The intended aim has thus been achieved: measurement in  
continuous mode and calibration of all the parameters  
of the measurement without interruption of the  
measurement.

30



Of course, the exemplary embodiments described are in no way limiting of the invention. Thus, no account has been taken, in the sequel of the description, of the disturbing fields mentioned in relation to figure 2. It  
5 is obvious that these disturbing fields may be eliminated by the method alluded to, based on the variations as a function of frequency, but which does not form part of the present invention.